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A COST EFFECTIVE ADVANCED EMISSIONS MONITORING SOLUTION FOR GAS TURBINES – STATISTICAL HYBRID PREDICTIVE SYSTEM THAT ACCURATELY MEASURES NITROGEN OXIDES, CARBON MONOXIDE, SULFUR DIOXIDE, HYDROCARBON AND CARBON DIOXIDE MASS EMISSION RATES

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ABSTRACT

U.S. Federal regulations under Title IV of the Clean Air Act Amendments promulgated in 1990 require continuous monitoring of nitrogen oxides (NO_x) and carbon dioxide emissions from large gas turbines. Local, regional, or State authorities may mandate continuous monitoring for carbon monoxide, sulfur dioxide, volatile organic compounds, and other specific pollutant parameters. U.S. regulations that require continuous emissions monitoring systems (CEMS) also allow for the use of predictive approaches as an alternative providing the installed predictive emissions monitoring system (PEMS) meets rigorous performance specification criteria and the site performs ongoing quality assurance tasks such as periodic audits with portable analyzers and annual accuracy testing. A statistical hybrid predictive emission monitoring system (PEMS) has been deployed at numerous sites in the United States to meet EPA requirements for continuous monitoring of gas turbine pollutant emissions. This paper discusses specific implementations of a unique cost-effective statistical hybrid PEMS on various classes of gas turbines ranging in size from 60kW to 180 MW, both gas-fired and liquid-fired units, in simple cycle and combined cycle mode of operation. The turbines were equipped with a variety of NO_x control strategies including dry low NO_x, steam and water injection, solid post-combustion catalyst, SoLoNO$_x$™, and selective catalytic reduction. In each instance the predictive engine operated on training data of at least three days and up to ninety days as required to develop a robust empirical model of the emissions. Each model was subsequently evaluated using standard U.S. EPA performance specification test methods. The results of PEMS performance testing on these gas turbines are presented along with additional information regarding the quality assurance and quality control procedures put in place and the costs to support the ongoing operation of the deployed compliance statistical hybrid PEMS.

1 INTRODUCTION

Federal regulations under Title IV of the Clean Air Act Amendments promulgated in 1990 (40 CFR Part 75) [2] require continuous monitoring of nitrogen oxides (NO_x) and carbon dioxide emissions from large gas turbines. Local, regional, or State authorities may mandate continuous monitoring for carbon monoxide, sulfur dioxide, volatile organic compounds, and other specific pollutant parameters under New Source Performance Standards promulgated in 1974 (40 CFR Part 60) [1]. U.S. regulations require continuous emissions monitoring systems (CEMS) and allow for the use of predictive approaches as an alternative providing the installed predictive emissions monitoring system (PEMS) meets rigorous performance specification criteria and the site performs ongoing quality assurance tasks such as periodic audits with portable analyzers and annual accuracy testing. PEMS have been used in the U.S. for gas turbine compliance monitoring under 40 CFR Part 60 for more than 20 years [3]. Prior to the promulgation of CEMS requirements in the U.S., gas turbine emissions were verified using simple parametric equations or manual stack test procedures (U.S. EPA Reference Methods) [1]. The pollutant emission rate from the turbine was typically measured (every one to five years) using these methods to determine the compliance status of the unit. Periodic testing was conducted with local regulatory agencies onsite to verify that the proper quality control procedures were applied. Compliance data prior 40 CFR Part 60 represented a momentary snapshot of the turbine emissions each year at best.

Manual test methods are not very efficient for continuous compliance determination. Regulatory agencies needed an alternative [5]. This need was first satisfactorily met using continuous emissions monitoring systems (CEMS) that utilize gas analyzers, calibration gases, and extractive sampling components. EPA began to require continuous monitoring of larger sources such as gas turbines with 40 CFR Part 75 [2].

Throughout this period of CEMS expansion, EPA has maintained procedures for certifying alternatives to CEMS such as PEMS [4], [6]. PEMS technology has evolved rapidly to meet these exacting requirements. Good quality CEMS data gathered over long periods of time enabled engineers to develop more complex models of gas turbine pollutant emission rates [7], [8], [9], [10], [11]. These theoretical first principle models have limited validity during startups, shutdowns, and transitional states [3]. Part 75 EPA mandates for continuous monitoring of primary pollutants from large gas turbines have largely been met with extractive CEMS [5]. PEMS to be used in emission trading programs must be demonstrated to provide data with equivalent accuracy as a CEMS and have model operating envelopes that include startup emissions. Recently, empirical PEMS have been certified as acceptable alternatives to CEMS for large frame gas turbine compliance under 40 CFR Part 75, Subpart E [12].

Modern empirical PEMS have also evolved to meet the need for continuous monitoring of gas turbine emissions at the lowest possible cost. PEMS can be significantly less costly to install, operate, and maintain than gas analyzer based continuous emissions monitoring systems which provide a known level of accuracy, drift, and downtime. There are performance specification tests and periodic audits such as the annual relative accuracy test audit that are equivalent in cost as those required of compliance CEMS, however, PEMS can provide years of service with little or no ongoing operational or maintenance cost once a robust model is developed [14].

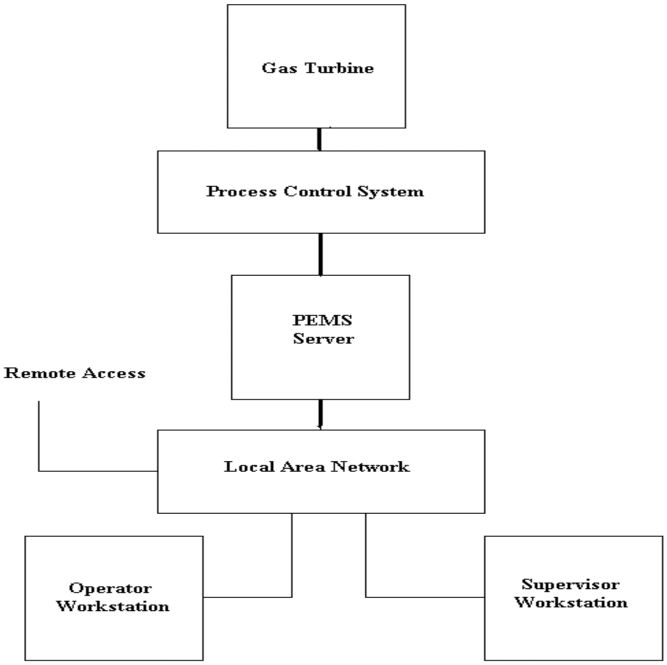


Figure 1: PEMS Block Diagram

2 PEMS CLASSIFICATIONS

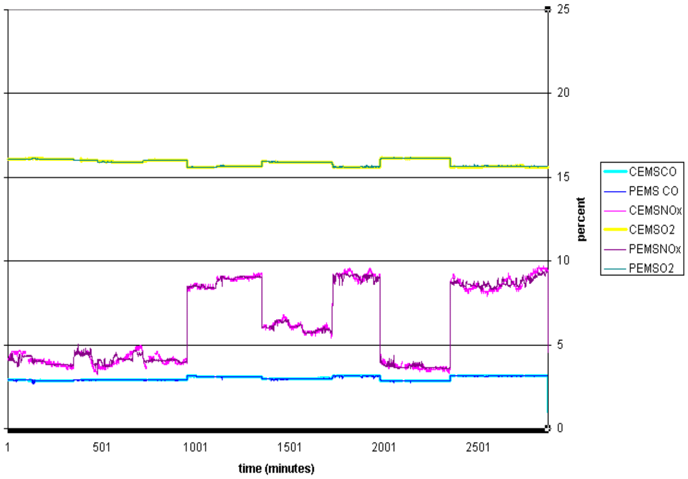
PEMS can refer to both parametric and predictive emissions monitoring systems. Parametric and predictive systems share a common functional relationship with the process and emissions (Figure 1). These approaches to emissions monitoring take in input data from the process control system and gas turbine instrumentation in place and generate emissions data without actually contacting the stack gas or analyzing its pollutant content in real-time [3], [16]. Although parametric and predictive emissions monitoring systems share a common functional block diagram, they provide dramatically different results.

A parametric system utilizes one to three key input parameters. Parametric systems utilizing three inputs or less are generally not very accurate and tend to over-predict the emissions. This includes the linear methods such as applying using emission factors which typically have a positive bias. Parametric systems require a few critical inputs that are used in formulaic calculations of the pollutant emission rate. A parametric formula is described for each pollutant, p, such that the emission rate, E, can be expressed as a function of up to three input parameters, I:

Parametric $E_p = f(I_1) \text{ or } = f(I_1, I_2) \text{ or } = f(I_1, I_2, I_3)$ (1)
Example $E_{NOx} = I_1 \times K_{NOx}$ where I_1 = heat input (2)

In this example the NO_x emission rate is defined as a linear function of heat input such as when applying an emission factor (K_{NOx}) to a low mass emitter or a peaking unit using Appendix E of 40 CFR Part 75 [2]. Parametric systems are not used on base-loaded gas turbines in U.S. emissions trading programs where continuous compliance monitoring is required such as under 40 CFR Part 75 [3], [15]. In this discussion, PEMS is restricted to the predictive type of system that can be used in U.S. compliance programs for continuous monitoring of all types of base-loaded gas turbines under Subpart E.

There are two primary types of predictive PEMS models: theoretical and empirical. The theoretical approach utilizes chemical or physical relationships and known laws of thermodynamics, for example, in a formulaic methodology. The first predictive systems used for continuous compliance were theoretical models known as complex ‘first principle’ methods [16]. A theoretical method uses a standard mathematical approach to resolve the multivariate relationship between key gas turbine inputs and the measured emission rate. These theoretical approaches were better than parametric systems, but not always accurate over long periods, in varying ambient conditions, if the fuel quality varied or when the unit aged. PEMS models have been deployed in the field based on a first principle approach only to be removed later due to problems with long term performance of the model [7], [8], [9], [10]. A typical hybrid model combines several of these theoretical approaches by weighting and aggregating the results to generate predictions for the target emission rate [13].



The hybrid approach using theoretical models has not passed the requirements of 40 CFR Part 75 to date. None of these theoretical approaches including first principle methodology have been certified by U.S. EPA 40 CFR Part 75, Subpart E.

Figure 2: Empirical $NO_x/CO/O_2$ PEMS Statistical Hybrid Results

2.1 EMPIRICAL PREDICTIVE SYSTEMS

Modern empirical predictive systems achieve very high levels of accuracy and can maintain that accuracy over many years. Empirical approaches (such as the neural network and statistical hybrid) require a historical dataset that is collected prior to deployment containing emissions data from CEMS and process data readily available from the turbine control system. A predictive formula is described for each pollutant, p, such that the emission rate, E, can be expressed as a function of n (greater than 3) number of input parameters, I, as:

Predictive $E_p = f(I_1, I_2, I_3, \ldots I_n)$ (3)
Example $E_{NOx} = f(I_1, I_2, I_3, \ldots I_n)$ or (4)
(Neural $E_{NOx} = I_1 \text{ x } w_1 + I_2 \text{ x } w_2 + I_3 \text{ x } w_3 + \ldots I_n \text{ x } w_n$ (5)
Network) where w_n is the weight for the input n

Empirical models use historical turbine operating data correlated with emission data to predict the emission rates in real-time with accuracy comparable to a CEMS [3]. Empirical systems have demonstrated accuracy equivalent to a CEMS. Several empirical approaches have been certified by U.S. EPA under 40 CFR Part 75, Subpart E [12]. In addition, these systems can be retrained when the combustion or pollution controls are modified or when the turbine is operated differently, for example a fuel switch to liquefied natural gas.

Empirical systems unlike parametric and other theoretical predictive systems utilized in the past for compliance can pass the requirements of Subpart E. Empirical systems utilize all the available unit-operating parameters and establish relationships between any quality assured input with significant correlation to the emission rate. The statistical hybrid PEMS accurately predicts the pollutant emission rate in real-time based on historical process and quality assured emission data.

The neural network is a complicated approach that requires specialized staff mobilized to the site to support certification along with significant testing both up front and periodically to maintain accuracy [11]. The values for the weighting factors used in equation (5) are adjusted by specialized technicians after an iterative process that involves testing the particular combination of weighting factors at various turbine loads prior to certification. The neural network can be as expensive to certify and maintain as a CEMS [3]. Likewise and similarly, first principle models require expert analysis and fine tuning of the derived equation and can also be very expensive to maintain. The formulations themselves require extensive knowledge of the gas turbine combustion process and instrumentation along with the mathematical model in order to make adjustments in the field [13].

2.2 STATISTICAL HYBRID PEMS MODEL

The statistical hybrid approach is an empirical predictive system that requires only a fixed sample of paired turbine and emissions historical training data. A statistical hybrid PEMS has the following features (see Figures 2 through 12):

- Robust model that is accurate across the full load range of the unit including all normal operating conditions and during transitional states such as startup and shutdown.
- Equivalent accuracy as a CEMS with superior reliability that is tied closely to the plant control system.
- Flexibility to be implemented using existing process instrumentation, interfaces, and control manufacturers.
- Can be certified as an alternative system under U.S. regulations for compliance monitoring of primary pollutants (40 CFR Part 60) [4].
- Can be assessed using quality control procedures defined to meet the requirements of U.S. EPA regulations for continuous monitoring [1], [2].
- Can be developed and retrained by non-technical onsite staff that tune or add data after a process or fuel change.
- Can be tested against EPA reference methods and has been demonstrated to meet 40 CFR Part 75, Subpart E [6], [12], [18].

The statistical hybrid method directly leverages the power and agility of the personal computer and a relational database containing paired historical emissions and process parameter data. It requires no specialized staff to develop or maintain. The model is a single deterministic method within a core application module. This module is the same for all turbine types, configurations, and control systems. The current state of the turbine is analyzed every minute at a minimum by the core module and an accurate emission rate is generated providing similar data exists in the historical training dataset [15].

Unlike the more complicated empirical systems such as neural network and first principle formulations used previously, the statistical hybrid model can be developed for any given gas turbine without a great deal of knowledge of the process or chemistry involved in the generation of pollutant emissions. A statistical hybrid predictive formula is described for each pollutant, p, such that the emission rate, E, can be expressed as a function of n number of input parameters depending on the availability of those input parameters, I, as:

Predictive $E_p = f(I_1, I_2, I_3, \ldots I_n)$ (6)
Example $E_{NOx} = f(I_1, I_2, I_3, \ldots I_n)$ or (7)
(Statistical $E_{NOx} = f(I_2, I_3, \ldots I_n)$ if Input1 fails or (8)
Hybrid) $E_{NOx} = f(I_1, I_3, \ldots I_n)$ if Input2 fails or (9)
$E_{NOx} = f(I_3, I_4, \ldots I_n)$ if Inputs 1 and 2 fail or (10)
$E_{NOx} = f(I_1, I_4, \ldots I_n)$ if Inputs 2 and 3 fail or (11)
… many other possible paths to prediction

The function, f, is fixed as the PEMS is deployed for compliance. The model is entirely dependent on the historical data. The training dataset can be derived from reference method or CEMS data and paired process data collected prior to certification. Data can be collected at any time and used to retrain the current model onsite in response to installation of pollution control equipment, variations in ambient conditions, or changes to standard operating procedures without the need for a specialist onsite. The flexibility of the statistical hybrid PEMS to utilize the widest variety of process inputs and interface directly with the process control system allows for the highest level of reliability and feedback to document the causes of and reduce emissions. Empirical statistical hybrid PEMS have been certified under 40 CFR Part 75, Subpart E [12].

The statistical hybrid model exploits the existing statistical relationships of the historical training dataset depending on the input parameters available and how they are represented in the empirical data [16], [17], [18]. The historical dataset is fixed prior to certification when used in compliance monitoring. This allows the PEMS to calculate a model envelope that defines the operating conditions represented in the historical training dataset. Alarms can be configured to detect when the turbine is operated outside the model envelope. All normal operating conditions including startups, shutdowns, and transitional states can be tested such that envelope excursions are minimized. This type of historical training dataset (containing all normal operating conditions) is deemed to be 'robust'. Robust statistical hybrid models produce minimal monitor downtime over long periods [16].

If a particular parameter is missing, the model utilizes the other available parameters to generate the prediction. This is the hybrid aspect of the model. Only inputs that are available, valid, and fall within the model envelope are used. The system can also generate predictions for these failed inputs. Procedures for validation of input data and replacement with predictions if failed are fixed in the core module. The fixed core application module (depending on the availability of turbine data and the model envelope) determines the output. The model is singularly deterministic in that for each input vector, representing the current turbine operating state, one accurate emission result is generated. This allows the PEMS to be tested against reference methods initially for certification and periodically for accuracy and quality control purposes.

Thus, an array of process input parameters is presented to the model in real-time. The core module of the PEMS assesses the current operating mode and generates predicted emissions from this dataset for the given set of input parameters (or lack thereof). The only difference between models deployed at the various sites is the parameter list and the data that was collected. Units of similar configuration with similar input parameters available can share data and models can be built of an entire class of gas turbines. Other than these unit and class specific configuration files, the method for generating the emissions data was the same in all cases. The method used in these demonstrations is not an algorithm, formula, or a first principle approach. It is a hybrid approach, but not a hybrid of several theoretical models. The model utilizes statistical relationships and a database, to generate predictions in a predefined way, but there are many ways to generate a prediction. Depending on the availability of the input parameters and their representation in the historical training database, predictions can be generated with one, two, three, or more inputs failing. The model envelope is defined within the historical training dataset which is fixed and therefore singularly deterministic in its compliance mode of operation.

Nomenclature

CEMS – Continuous Emissions Monitoring System or a gas analyzer based system (with analog output proportional to the emission rate) and sample handling equipment, calibration controls, and separate data acquisition components.

PEMS – Predictive Emissions Monitoring System or a software based solution that generates predicted emissions data from turbine operating data and sensors available to the turbine control system that is not a parametric approach.

Parametric Systems – Non-continuous emissions monitoring that uses three or fewer input parameters with limited accuracy and a theoretical formula with positive bias.

40 CFR, Part 60 – U.S. New Source Performance Standards for industrial and commercial sources published under the Code of Federal Regulation of the United States.

40 CFR, Part 75 – U.S. Clean Air Act Amendments instituted under Title IV the Acid Rain Provisions for electrical generating sources published under the Code of Federal Regulation of the United States.

PS-16 – Performance Specification 16 for predictive emission monitoring systems used in compliance with 40 CFR Part 60 New Source Performance Standards.

Subpart E – Certification and performance specification tests with submittal instructions for alternative monitoring systems used in compliance with 40 CFR Part 75.

3 GAS TURBINE CLASSES

The statistical hybrid PEMS, an empirical model completely defined by its historical training dataset has been applied to a variety of classes of gas-fired turbines from the smallest micro-turbines to the largest frame generators. The same core module with statistical hybrid predictive engine was deployed in each instance. Gas turbines included in the study range in size from 60kW – Capstone C60, 1.1 MW – Kawasaki M1A-13D, Solar Mars, Solar Taurus, Solar Titan, GE Frame 5, GE Frame 6, GE 6B/E, GE LM2500, GE LM6000, GE Frame 7, GE 7FA, and Siemens V84.

3.1 MICRO AND MINI TURBINES

The statistical hybrid PEMS was applied to a micro-turbine (Capstone C60). The capstone micro-turbine was equipped with a statistical hybrid PEMS and subjected to performance specification testing. The PEMS successfully passed the certification tests and provided real-time and historical emissions. The statistical hybrid PEMS was applied to a simple cycle gas turbine (Kawasaki) with the support and equipment provided by Horiba Instruments, Inc. The turbine with post-combustion catalytic controls was equipped with a statistical hybrid PEMS and subjected to performance specification testing. The PEMS successfully passed the certification tests of 40 CFR Part 60 NO_x and CO emissions.

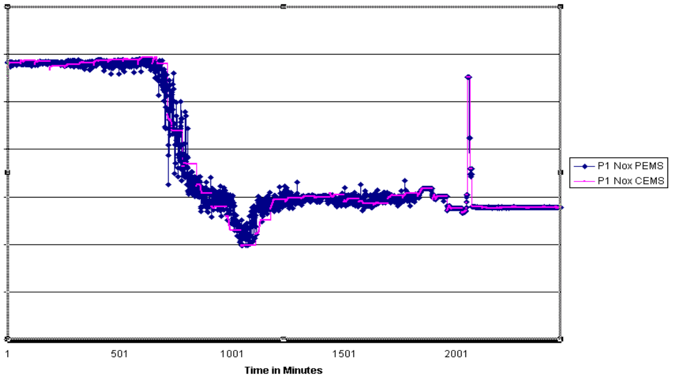


Figure 3: Solar Titan NO_x PEMS

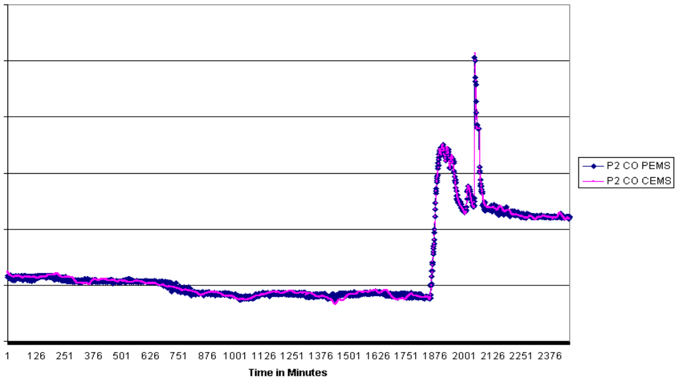


Figure 4: Solar Titan CO PEMS

3.3 SMALL TURBINES

The statistical hybrid PEMS was applied to several small turbines less than 25 MW (Solar Mars - see Figure 2, Solar Taurus, and Solar Titan – see Figure 3 through 7). The turbines were tested at the factory prior to shipment in the final integration stage of the package. Each unit was run up and down in load under lean and rich fuel conditions. A PEMS model was built on the initial factory test data and validated in the final emissions testing. The PEMS successfully passed the performance tests and provided real-time and historical emissions predictions for each small turbine class. Pollutants evaluated include nitrogen oxides (Figure 3 - NO_x), carbon monoxide (Figure 4 - CO), carbon dioxide (Figure 5 – CO_2), total volatile organic compounds or hydrocarbons (Figure 6 – HC), and oxygen (Figure 7 - O_2). The small turbine PEMS was also trained with data from oxygen, carbon monoxide, and total hydrocarbon gas analyzers. This data was used in the historical dataset and allowed the PEMS to accurately model these emissions. The model configuration provided accurate emission predictions for all parameters using one singular methodology for all units.

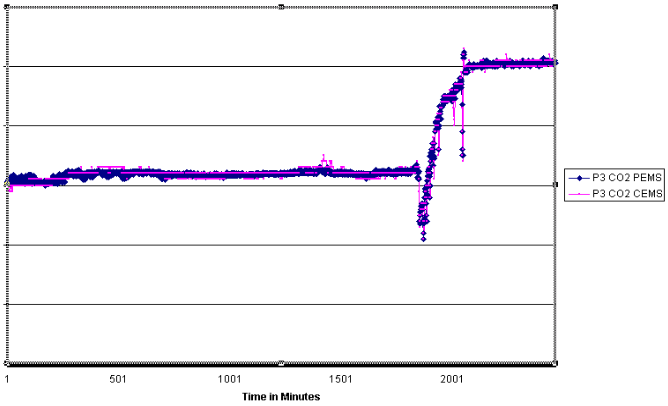


Figure 5: Solar Titan CO_2 PEMS

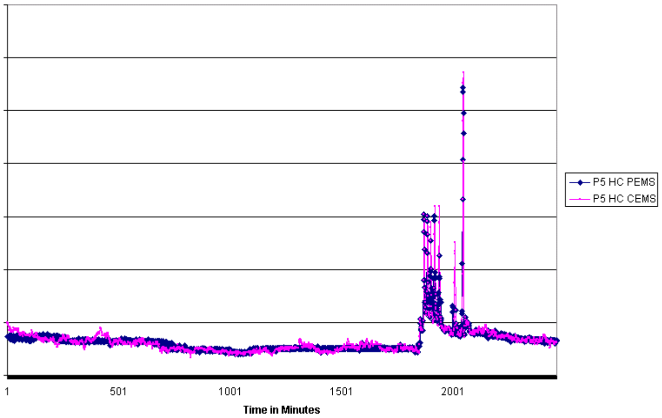


Figure 6: Solar Titan HC PEMS

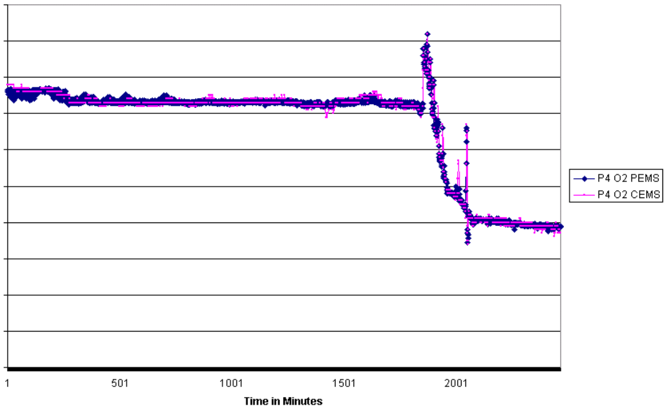


Figure 7: Solar Titan O_2 PEMS

3.4 MID TO LARGE FRAME TURBINES

The statistical hybrid PEMS was applied to a larger gas turbines in the range of 50 MW to 180 MW power generation capacity. The turbine sizes included GE Frame 7 and Siemens V84, some of the largest gas turbines manufactured. These turbines were equipped with a variety of modern pollution control technologies including DLN, steam and water injection, and SCR. A variety of control systems were used.

A PEMS was deployed in each case along with a CEMS to collect continuous emission monitoring system data. Following the collection of the required 720 operating hours on each unit, a Subpart E application was prepared and submitted to the Administrator of U.S. EPA approval of the installed PEMS on the simple and combined cycle turbines.

The alternative monitoring system was installed just prior to the start of the Subpart E demonstration to determine average hourly emission data for NO_x using a statistical hybrid model as specified under Subpart E of 40 CFR, Part 75. The data from each of the units was pooled to create one master PEMS historical training dataset or model (Figure 8). The data presented in this class certification is from one single model that covers all six units. Following the demonstration run on all units, the data confirmed that the installed alternative monitoring system has the same or better precision, reliability, accessibility, and timeliness as that provided by the CEMS.

4 SUBPART E TESTING METHODOLOGY

Certification under 40 CFR Part 75 requires a Subpart E demonstration and comparison of the data with a quality assured CEMS. The temporary CEMS were operated throughout the required 720 hour demonstration to compare with the PEMS. The initial certification consisted of a single-load (9-run) data set using EPA Method 7E and Method 3A. Each certification test included a nine run RATA. Data from the reference method tests were used to generate a relative accuracy result against the installed temporary CEMS and also the PEMS. The PEMS and CEMS were operated normally during the Subpart E demonstration.

Field data and notes were collected during each day of operation and daily calibrations were performed. At the conclusion of these demonstrations, the relative accuracy test audit was repeated using reference method data from EPA Method 7E and Method 3A to assess the accuracy of the installed PEMS. The CEMS data was calibration drift adjusted and time-correlated to the PEMS data for the Subpart E analysis. PEMS data was produced in minute increments, but averaged hourly for analysis. Similarly, the CEMS data was collected and averaged by the minute and secondarily by the hour. Statistical analyses were performed and graphs of the results were plotted based on the paired hourly data sets consisting of a minimum of 720 records for each unit firing natural gas only.

Performance specification testing was conducted to assess the quality and accuracy of data generated by the CEMS and PEMS. The performance specification test procedures under Subpart E are detailed in U.S. EPA 40 CFR Part 75, Appendices A, B, and F. A certification was performed using the applicable test methods including the relative accuracy audit. Daily calibration at two levels was conducted each operating day.

INPUT	DESCRIPTION	MIN	MAX
Input14*	Mega-Watt Load	0.00	63.9
Input29*	Gas Flow	0.00	38445.2
Input10	Guide Vane Position	50.20	84.4
Input13	Firing Temperature Reference	0.0	1997.7
Input15	Fuel Stroke Gas	0.0	73.1
Input17	Fuel Stroke Reference	0.0	74.5
Input24	IGV Temperature Cont Rev	0.0	1259.9
Input25	Average Exhaust Temp	74.06	1099.0
Input3	Bell-mouth Differential Pressure	0.00	68.6
Input4	Comp Discharge Pressure	0.00	132.6
Input6	Air Flow	0.0	548.6
Input7	Air Flow Dry	0.0	546.5
Input19	Splitter Valve Position	0.0	101.0
Input30	Turbine Exhaust Press	0.0	16.55

Figure 8: Model Envelope

4.1 DESCRIPTION OF CEMS EQUIPMENT

The temporary CEMS were quality assured and certified using the specifications in 40 CFR Part 75. The CEMS consisted of a heated probe and filter, heated sample lines, conditioning system, analyzers, and a data acquisition system. The CEMS instrumentation consisted of a chemiluminescent NO_x analyzer and a zirconium oxide oxygen analyzer. The CEMS was outfitted with a data acquisition system and certified calibration gases. The data acquisition system was used to collect the required 720 hours of comparison data.

The heated sampling probe was equipped with an appropriately sized probe pipe and placed in the center of the turbine exhaust duct. Care was taken to ensure the sample was properly heated (>300 deg. F) prior to the sample conditioner. The sample was conditioned to remove moisture (<5 deg F) and presented to the analyzers. Calibration was achieved by sending calibration gas to the probe tip and measuring the response from the stack using the normal sample path at normal sampling temperature, pressure, and flow rates.

4.2 CEMS DRIFT TESTING

The temporary CEMS were operated under normal conditions for a minimum period of seven days prior to certification. The magnitude of the Calibration Drift (CD) was determined at the same time each day using certified (EPA protocol 1) calibration gases. A cylinder of UHP nitrogen (zero gas), and cylinders of approximately 80% span NO_x and approximately 80% span O_2 was used. In addition, a lower level NO_x gas was used of approximately 20 ppmv NO_x.

The calibration gas was introduced to the sampling train near the probe and allowed to pass through the sample delivery and conditioning system during normal turbine operation. The response to the daily calibration gases were measured and recorded. The CEMS was automatically calibrated each day during normal operation at the specified time. No adjustments to the analyzers or DAS were made during the week of performance testing for certification. The differences between the calibration value and the response were used to calculate the daily calibration drift and to correct the raw data for use in the training dataset and statistical analysis.

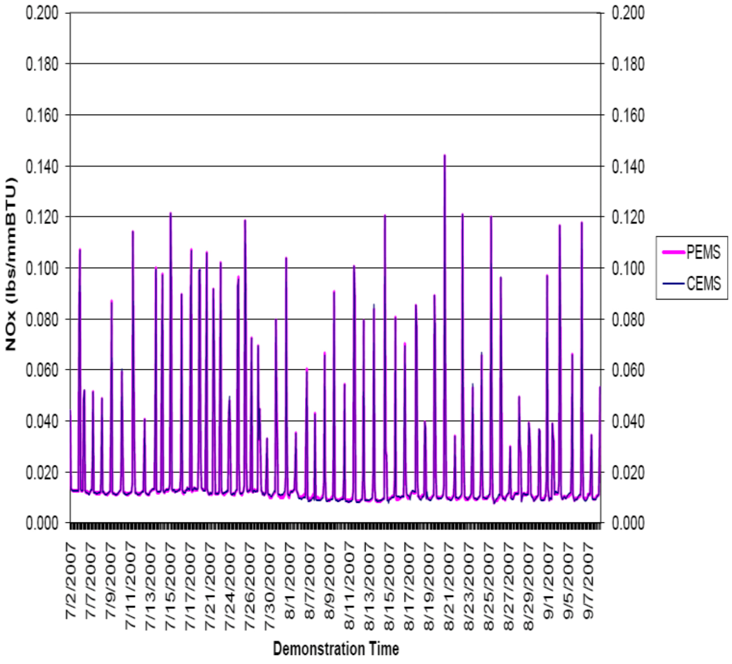


Figure 9: Time Plot PEMS vs. CEMS (Large Gas Turbine)

4.3 CEMS PERFORMANCE TESTING

The linearity error tests were conducted prior to the Relative Accuracy Test Audit. The CEMS was challenged with EPA protocol 1 gases while operating normally. The audit gases were introduced to the CEMS at the probe tip and allowed to pass through all normal sample delivery and conditioning components. The CEMS were challenged three times with each of the audit gases (low, mid, and high levels for each of the two NO_x ranges used and the O_2 range) as specified in the test methods. The final responses of the analyzers were recorded. The CEMS were challenged with EPA protocol 1 gases while the CEMS was operating normally. The audit gases were introduced to the CEMS at the probe tip and allowed to pass through all normal sample delivery and conditioning components. Low-level gas was introduced first and the CEMS allowed to stabilize. An upscale audit gas was introduced to the CEMS probe and the time to reach 95% of the audit value was recorded. A downscale audit gas was introduced next and the time to reach within 5% of the audit value was recorded. The procedure was repeated three times for each audit gas. The response time was determined as the maximum of the three test values.

4.4 CEMS and PEMS RELATIVE ACCURACY

Following completion of the calibration error and response time tests, the relative accuracy tests were conducted. U.S. EPA Reference Methods 3A and 7E were performed as specified in 40 CFR, Part 60, Appendix A. A minimum of nine test runs were completed for a duration of 21 minutes using Method 3A to determine the Oxygen content and Method 7E to determine the nitrogen oxides content of the stack gas exhaust. The reference method test probe was located in the turbine exhaust stack near the CEM probe. NO_x emission rates were calculated using U.S. EPA Method 7E and compared to the CEMS and PEMS values for the same time periods. Hour averages were evaluated graphically (Figure 9).

The nitrogen oxides and oxygen values were compared to the CEMS values and used to calculate the nitrogen oxides emission rate in pounds per million BTU. The mean of the reference method nitrogen oxides emission rates, the mean of the CEMS emission rates, and the differences between the reference method and CEMS rates were calculated for each test run. The difference, standard deviation, confidence coefficient, and relative accuracy was calculated from the 9-run data sets using the equations presented in 40 CFR, Part 75, Appendix B.

4.5 STATISTICAL ANALYSIS

The PEMS and CEMS data are compared using standard statistical analytical methods. The correlation coefficients of the CEMS and predicted PEMS NO_x mass emission rates ranged between 0.94 and 0.99. The single model also passed the t-test and F-test for each unit as defined in Subpart E of 40 CFR Part 75 [6]. Detailed results of these tests have been presented previously [12], [17], 18].

4.6 CEMS vs. PEMS GRAPHICAL ANALYSIS

The PEMS and CEMS are compared using several graphical representations of the data prescribed in 40 CFR Part 75, Subpart E. The time plot (Figure 9) shows the PEMS and CEMS response on the same axis. The X Y plot depicts the CEMS vs. the PEMS in a format where the PEMS is on the y axis and the CEMS on the x axis. The data analyzed and presented graphically was averaged by hour (Figure 10).

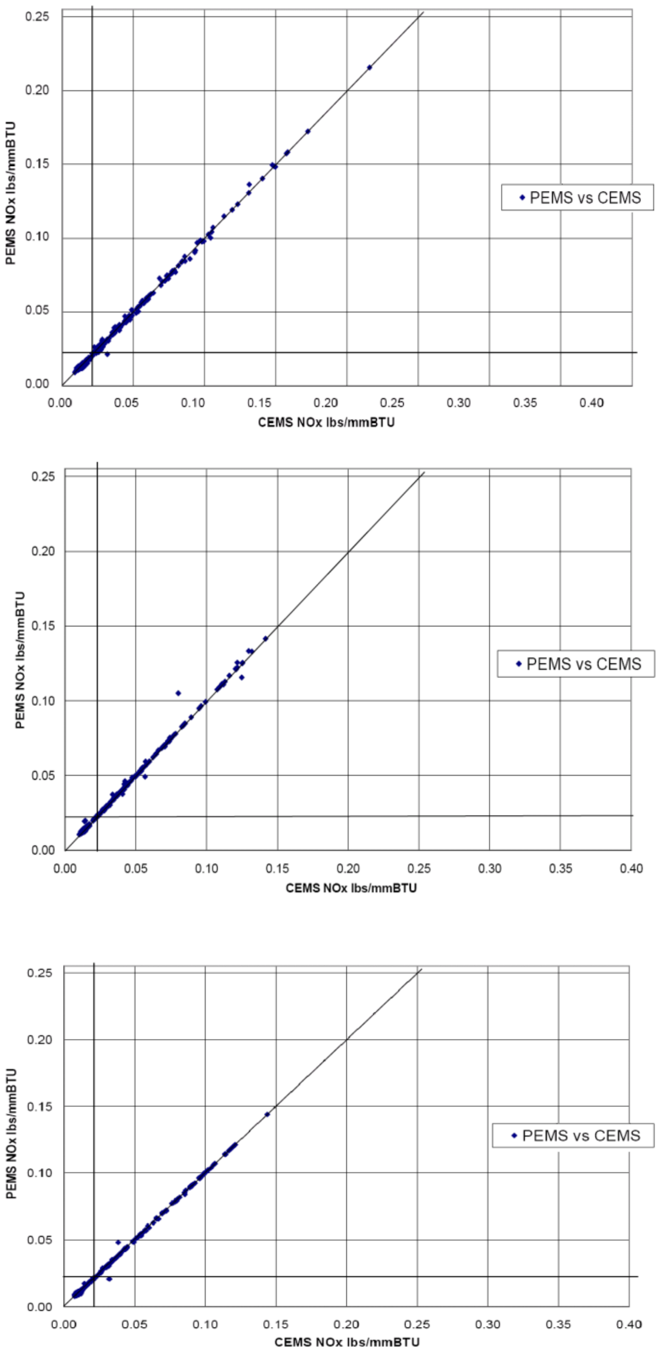


Figure 10: X Y Plots of PEMS vs. CEMS (Mid Turbine)

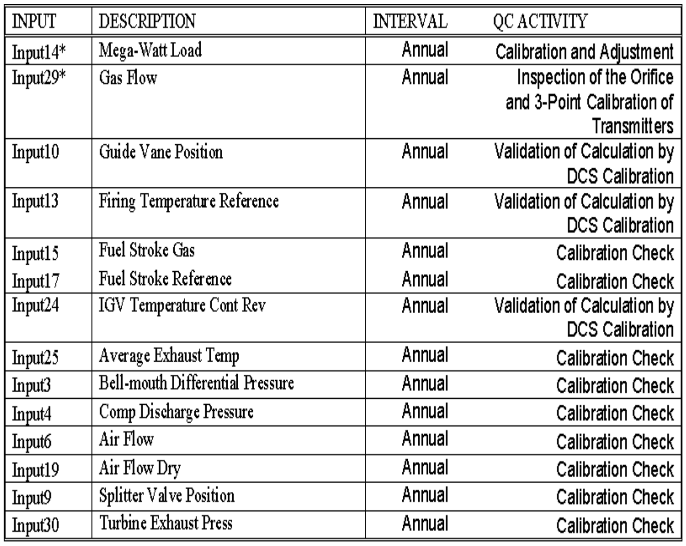
5 PEMS QUALITY ASSURANCE

A quality assurance program is established for each site and for each pollutant parameter or critical input parameter used in the deployed compliance monitoring system. The instrumentation used in the PEMS model was subjected to a minimum annual check and calibration (Figure 11).

The statistical hybrid PEMS interfaces directly with the process control system for data acquisition. A Quality Assurance program is put in place in accordance with 40 CFR Part 75, Appendix B or 40 CFR Part 60, Appendix B. The Quality Assurance Manual is located next to the PEMS server. System maintenance, database maintenance, and data backup procedures have been instituted onsite and are conducted quarterly. All PEMS quality control activities are documented in the Quality Assurance Manual.

Each operating day, the PEMS is evaluated at startup, each hour during any given load condition, and during shutdown or transition to new load. The PEMS is evaluated for concurrence with the turbine control system display using each of the following ‘critical compliance’ parameters (unit load, gas flow, combustion temperature, exhaust temperature and pressure for example). These inputs are used by the PEMS to determine the NO_x emission rate. Any significant deviation as displayed by the turbine control system is noted and the OEM supplier is called onsite to make corrections.

In addition to the daily quality control review, periodic quality control procedures as specified in 40 CFR Part 75, Appendix B for the turbine are utilized. These quality control activities include an annual inspection/calibration of the orifice plate used for the gas flow input signal. The temperature and pressure compensation sensors used by the process control system to correct the gas flow to standard conditions are calibrated each quarter.



INPUT	DESCRIPTION	INTERVAL	QC ACTIVITY
Input14*	Mega-Watt Load	Annual	Calibration and Adjustment
Input29*	Gas Flow	Annual	Inspection of the Orifice and 3-Point Calibration of Transmitters
Input10	Guide Vane Position	Annual	Validation of Calculation by DCS Calibration
Input13	Firing Temperature Reference	Annual	Validation of Calculation by DCS Calibration
Input15	Fuel Stroke Gas	Annual	Calibration Check
Input17	Fuel Stroke Reference	Annual	Calibration Check
Input24	IGV Temperature Cont Rev	Annual	Validation of Calculation by DCS Calibration
Input25	Average Exhaust Temp	Annual	Calibration Check
Input3	Bell-mouth Differential Pressure	Annual	Calibration Check
Input4	Comp Discharge Pressure	Annual	Calibration Check
Input6	Air Flow	Annual	Calibration Check
Input19	Air Flow Dry	Annual	Calibration Check
Input9	Splitter Valve Position	Annual	Calibration Check
Input30	Turbine Exhaust Press	Annual	Calibration Check

Figure 11: Quality Assurance Program Summary

A fuel sampling and analysis program is developed for each site and for each of its turbines. This program includes a monthly sampling of the pipeline natural gas supply. Gas sample data is entered into the PEMS and used to verify sulfur content at the prescribed level for reporting the heat input level. A fixed gross caloric value for the pipeline natural gas is typically used by the PEMS model, although in some instances an online analyzer is used to provide a continuous measurement of the fuel heat content, sulfur content or quality.

6 PEMS vs. CEMS OPERATING EXPENSE

The initial and long-term costs for a PEMS can be substantially lower than those of a CEMS. The initial cost for a PEMS usually ranges from one-third to one-half that of a CEMS [14]. This varies depending on the PEMS provider. If the PEMS requires specialized support from 'experts' and a great deal of testing to develop and maintain, the overall cost of an empirical PEMS can be comparable to a CEMS primarily due to the costs associated with additional upfront partial load testing [3]. Once a robust empirical model is developed, the objective when deploying a PEMS is to have a continuous monitoring system that is both reliable and very cost-effective in the long term. Again, if experts are required to be onsite each time the PEMS is audited or needs adjustment, the maintenance costs can also be significant. Some PEMS require minimal maintenance and support once developed.

A PEMS can provide accuracy that is more reliable than a CEMS. PEMS do not drift. PEMS rely on process inputs and instruments that typically drift no more than 1% to 2% per year. A typical model will use 10 or more input parameters that are in some cases redundant such that the impact of drift is further minimized. The resulting emissions prediction is resilient to input failure and drift such that no single input parameter is critical to the accuracy of the predicted emission. CEMS analyzers can drift 1% to 2% daily. Long-term CEMS drift is experienced through contamination of sample transport and the sampling train and component failure. Total CEMS system drift is associated with the sampling probe, transport and conditioning system, sample line, temperature control, ambient conditions, and analyzer drift. Each of these contributes directly to total system drift or CEMS inaccuracy.

PEMS have lower startup costs. Installation of a PEMS requires the installation of a computer with the PEMS software that is interfaced to the gas turbine control system. Normally one day onsite or less is required to startup a PEMS including hardware installation [14]. Depending on complexity and location of the CEMS, delivery generally is 90 to 120 days at best and installation up to 14 additional days after all the equipment arrives onsite using skilled trades to install ports, probes, umbilical, cable tray, CEMS rack, environmentally controlled shelter or area, gas cylinders, cylinder racks, gas tubing runs, drain and exhaust lines, plus interconnecting wiring and low dew point clean air supply.

PEMS require less spare parts and onsite training than CEMS. CEMS training is usually three to five times longer in duration and scope as PEMS training. PEMS should require no on site emergency service. A direct modem to the system should take care of most problems incurred. On site emergency service for a CEMS is inevitable and typically expensive.

PEMS do not rely on any one process input to maintain system uptime or accuracy of emissions data quality. The PEMS uses numerous and redundant inputs obtained from a direct interface to the turbine control system. Therefore, very little, if any, down time or missing data should ever be reported. CEMS typically are considered doing well if they maintain 95% uptime which is a minimum requirement. If an analyzer fails (NO_x, CO or O_2 etc) or a critical sampling component fails, the system is consider down and down time is logged. Emergency service can and will be required.

PEMS can display process and combustion efficiency reports. CEMS do not. CEMS provide information about the content of stack gas emissions and do not typically provide process data or combustion efficiency. PEMS can be used to determine the source(s) of excess emissions. CEMS do not. Combustion input parameter(s) that are out of normal range can be identified and provide critical information to avoid excess emission events. CEMS do not provide any insight as to the cause of an excess emission nor do they have the ability to facilitate process control adjustments or correction of the problem. Although an operator may track the emissions as they change, CEMS cannot point the operator to the cause or the potential solution to the excess emission event.

7 CONCLUDING REMARKS

Advanced empirical methods have been successful at meeting the requirements of U.S. emission trading programs such as EPA Title IV Acid Rain (40 CFR Part 75) regulations that require continuous monitoring for nitrogen oxides to demonstrate base-loaded gas turbine compliance. Empirical PEMS achieve very high accuracy levels and have demonstrated superior reliability in gas turbine applications under existing U.S. air compliance regulations. PEMS can be certified as an alternative to gas analyzers for gas turbine compliance in the United States. Advanced empirical PEMS can be expensive to install and maintain. The statistical hybrid PEMS is flexible and resilient to input failure retaining excellent accuracy across the whole range of ambient and operational conditions such as startup, shutdown, and other transitional turbine states. Experts and specialized staff are not needed to develop or maintain the statistical hybrid model reducing the total cost of gas turbine compliance monitoring program when compared to a CEMS or other complicated empirical methods such as a neural network or a multivariate first principle model. A robust statistical hybrid model is a cost-effective continuous monitoring solution for gas turbine compliance in U.S. emission trading programs.

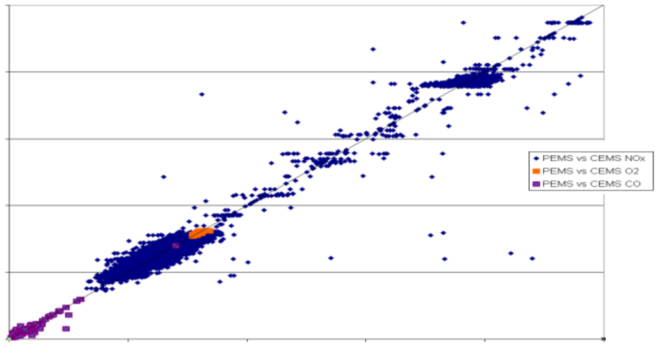


Figure 12: Statistical Hybrid PEMS Minute Data (Gas Turbine Example – nitrogen oxides, carbon monoxide, and oxygen)

8 ACKNOWLEDGMENTS

Most of the supporting data for the Subpart E certifications can be found in the EPA docket first published for comment in 2005 [18]. We would like to acknowledge the contributions of Mr. Dave Haehnle and Mr. Mike Roth of CMC Solutions and the efforts of the U.S. EPA Clean Air Markets Division and CMC business alliance partners.

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